Tracking and Vertexing at CMS

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Additional information in:

6 - CMS detector status and commissioning
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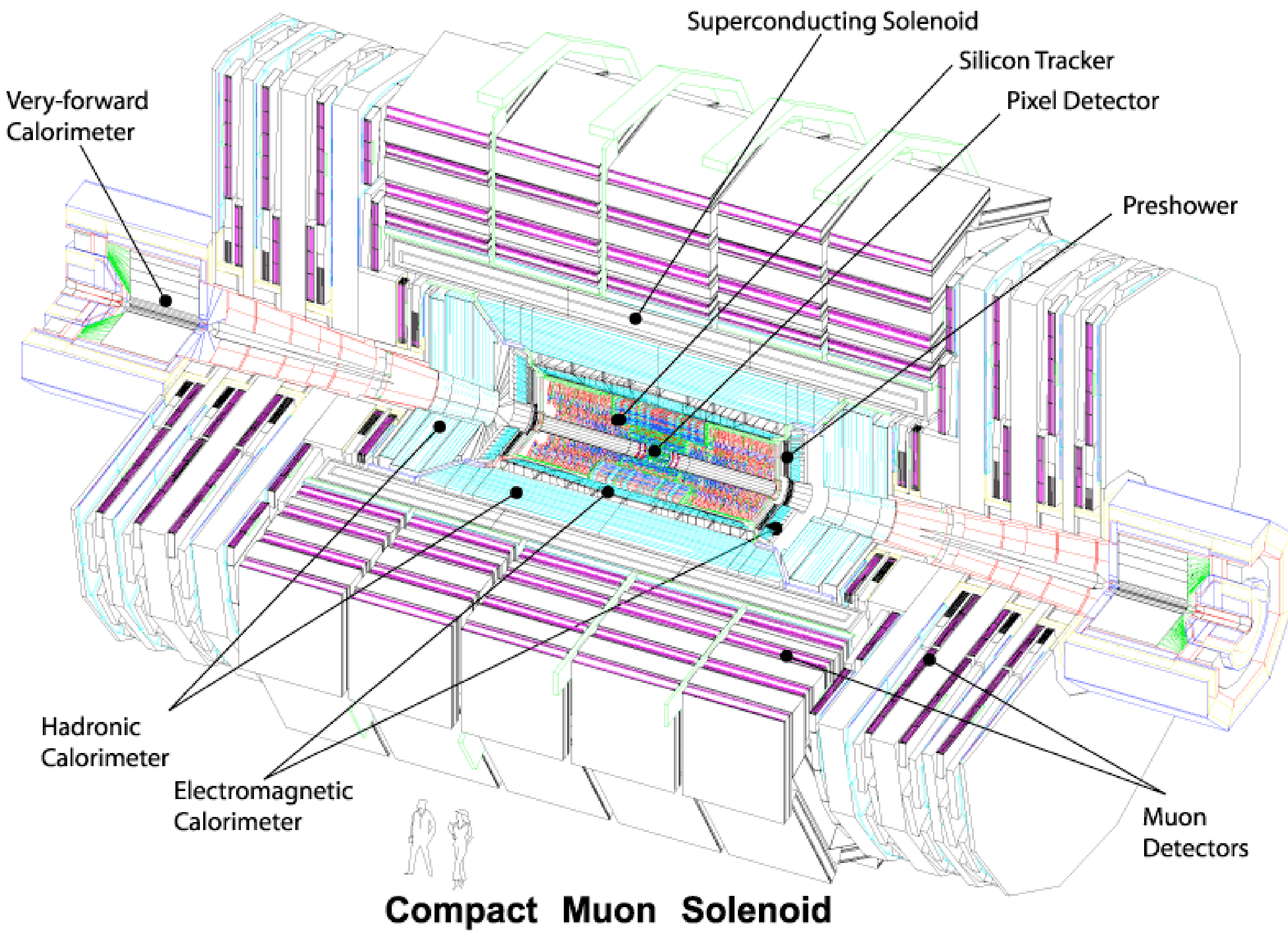
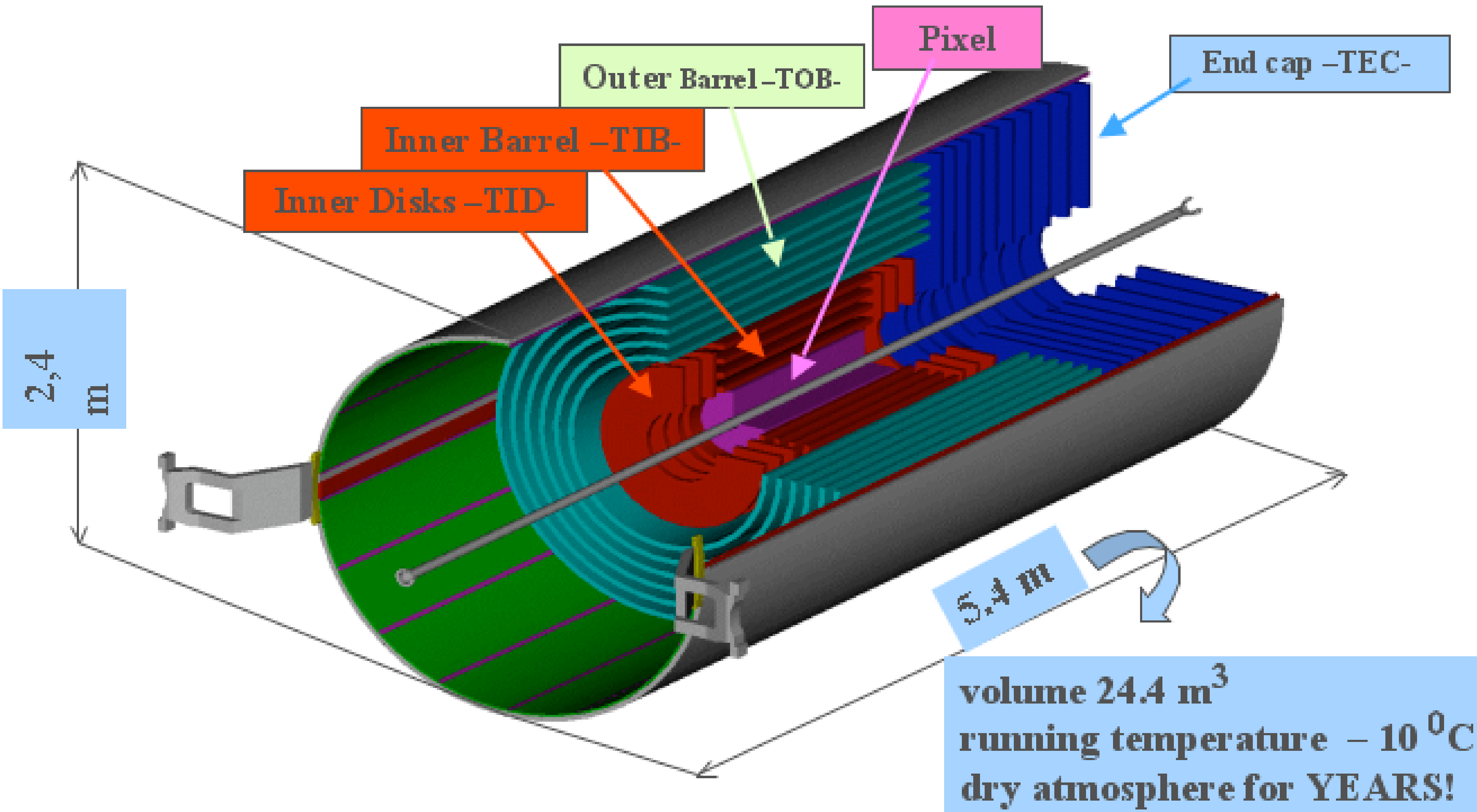
The CMS Detector

- Inner tracking detectors small, colorful region of drawing below
- Shares 4 Telsa solenoid field (2.7 GJ!) with electromagnetic and hadronic calorimeters -> outer tracking layer at r ~ 110 cm
- 1.9 mm sagitta for p_T = 100 GeV/c tracks (190μ for 1 TeV/c)

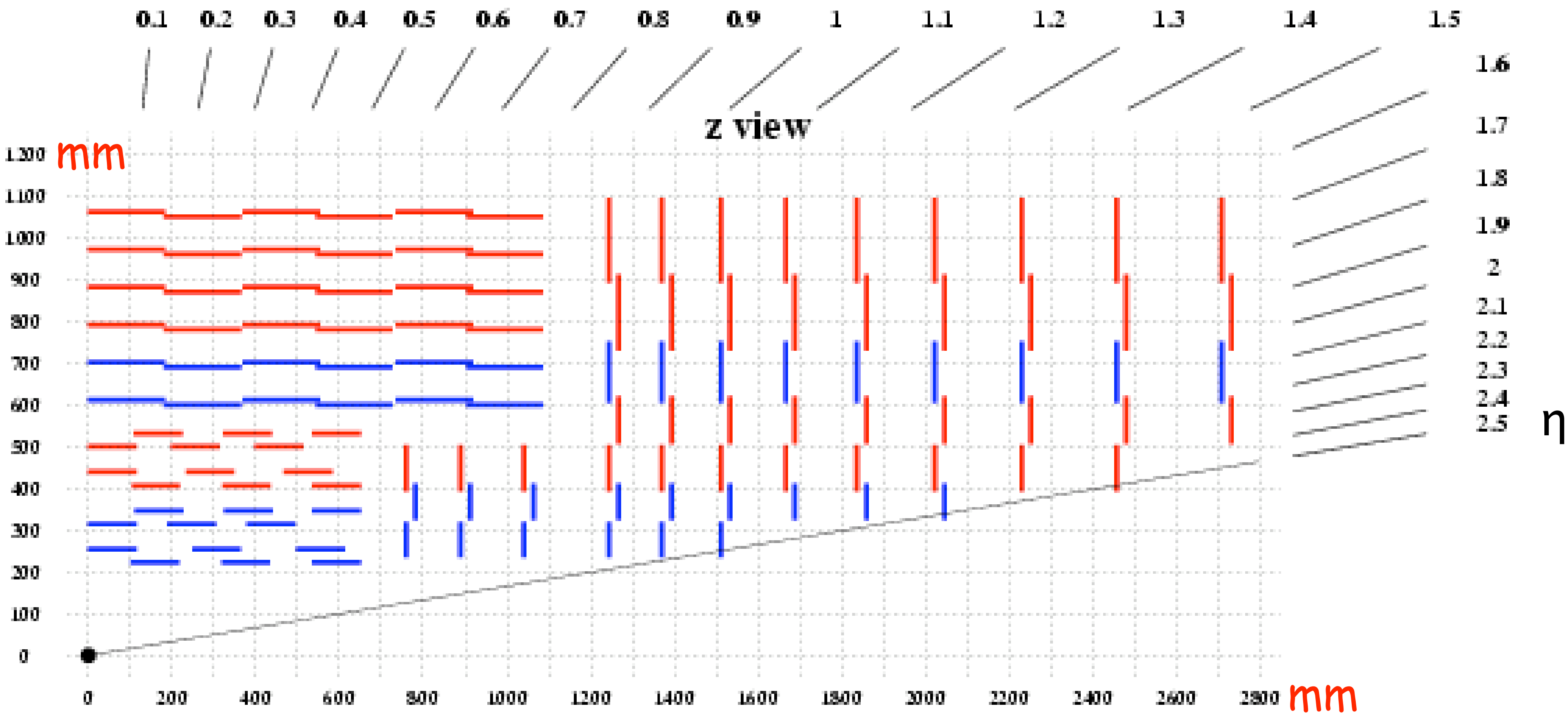


The CMS Tracking Detectors

- At design L (10^{34} $cm^{-2}s^{-1}$) have 20 min-bias events/(25 ns bunch x-ing)
- N/(25 ns×cm^2) ~ 5 at r = 4.4 cm (need pixels), ~ 0.1 at r = 25 cm (strips OK). Need fast response time
- Extreme radiation environment -> design for bulk type inversion and keep cold. Pixel and strip assemblies all have C_6F_{14} cooling loops



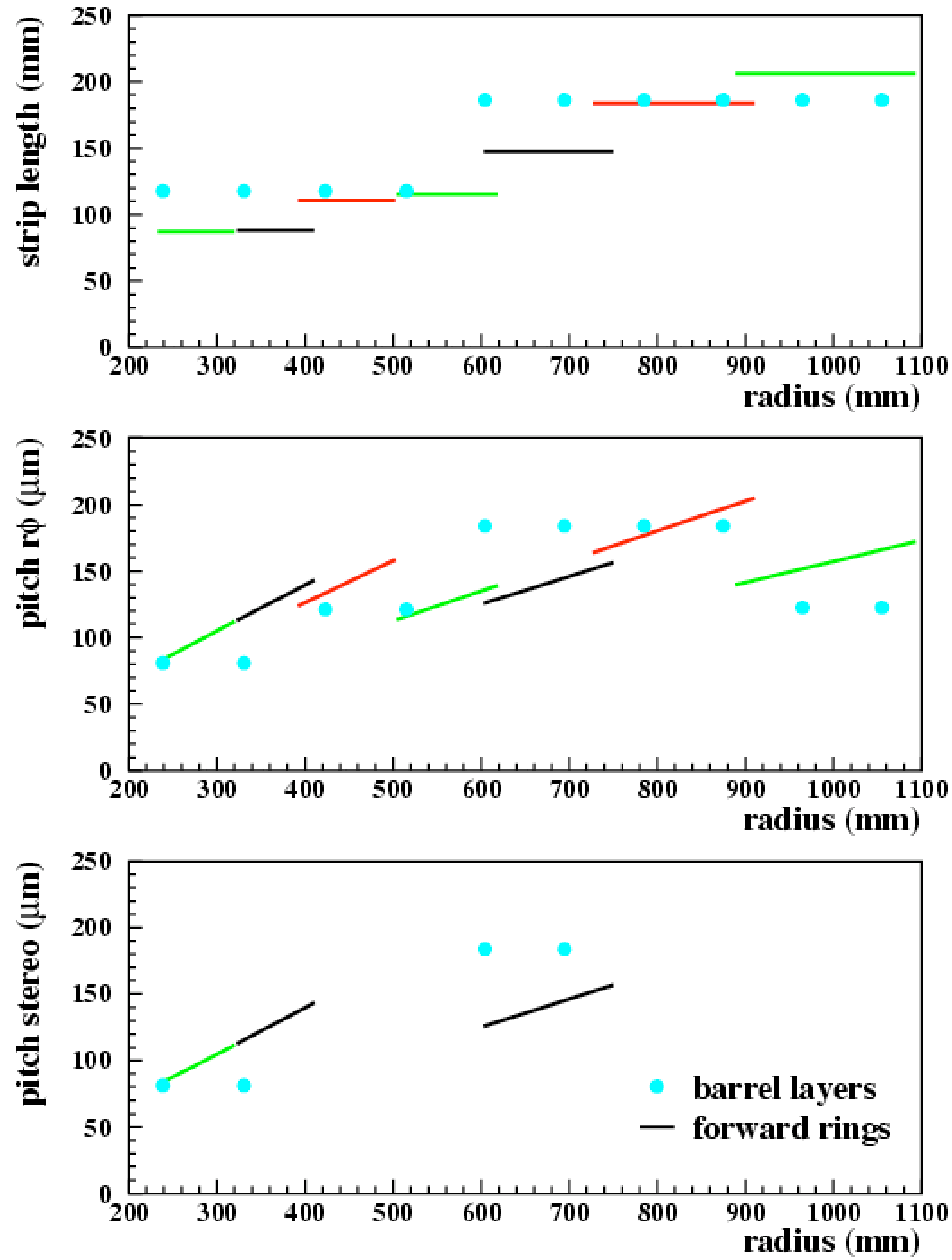
The CMS Si Strip Trackers



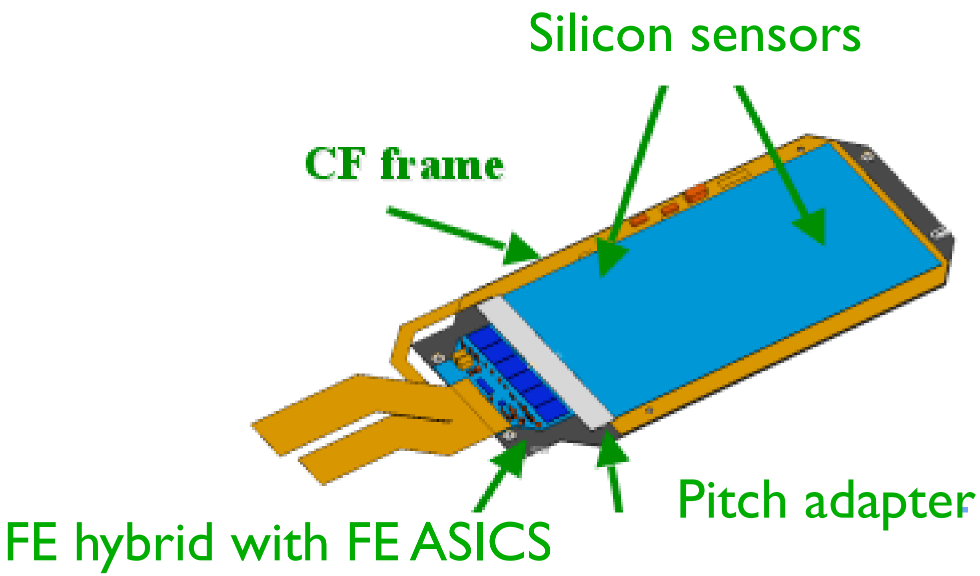
- Red are single-sided (axial, radial) sensor modules
- Blue are double-sided (glued single-sided with small stereo angle)
- 440 m^2 of Si wafer, 210 m^2 covered with sensor, 10M channels. All ~16000 modules finished May 2006

Strip Tracker Layout

- Keep it reliable - single-sided, AC coupled, polysilicon biased
- Thin (320 µm) sensors for r < 60 cm, thick (500 µm) sensors for r > 60 cm
- <100> crystal less sensitive to radiation damage than <111>
- Keep width/pitch low (~0.25), ~constant for low capacitance, independent of pitch and thickness
- After irradiation, expect S/N ~ 13 for thin, ~15 for thick sensors



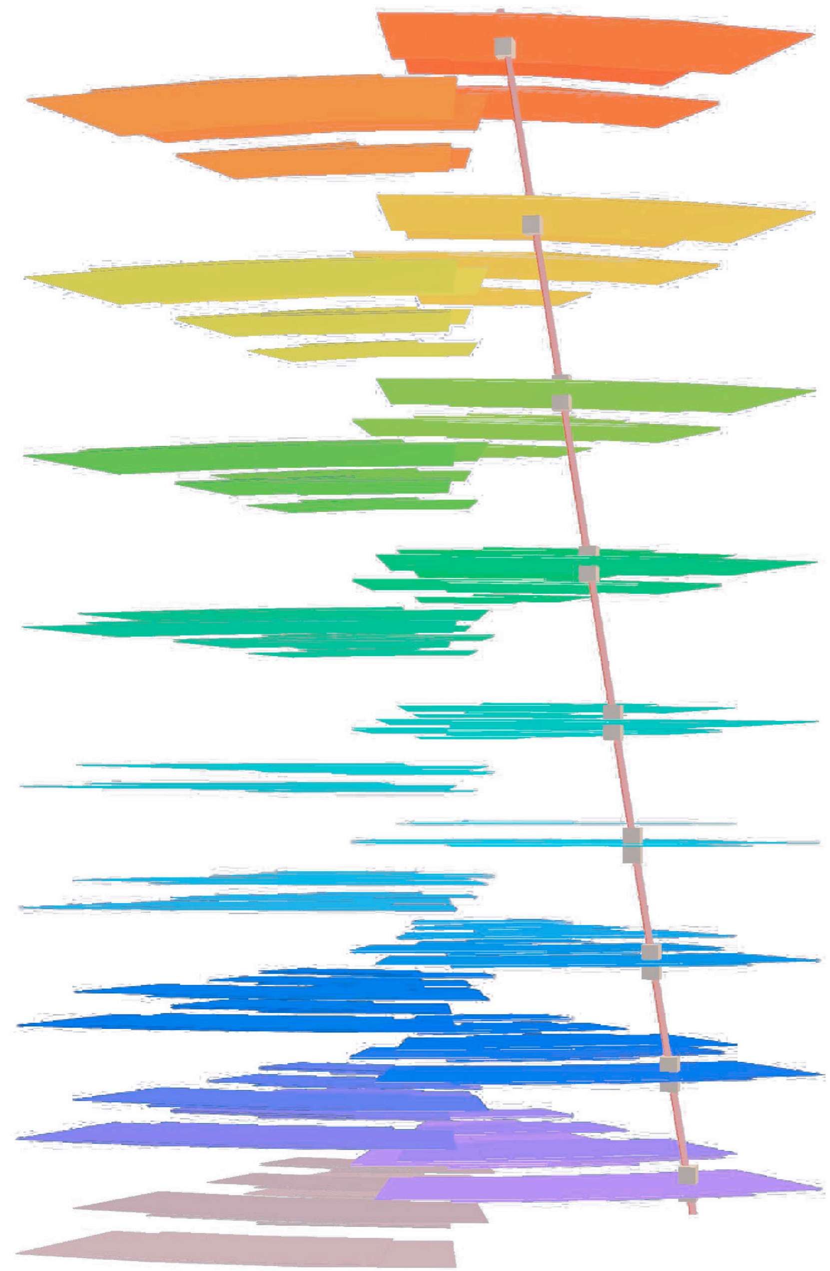
Barrel Strip Trackers (TIB, TOB)



- Strips read out by APV ASIC (75376 total) connected thru a glass pitch adapter
- APV has peak (one sample) and 3 sample (for beam x-ing info) modes
- TIB modules, TOB RODs held in place by CF support structures
- Photo left is an early production ROD of double-sided modules in fixture

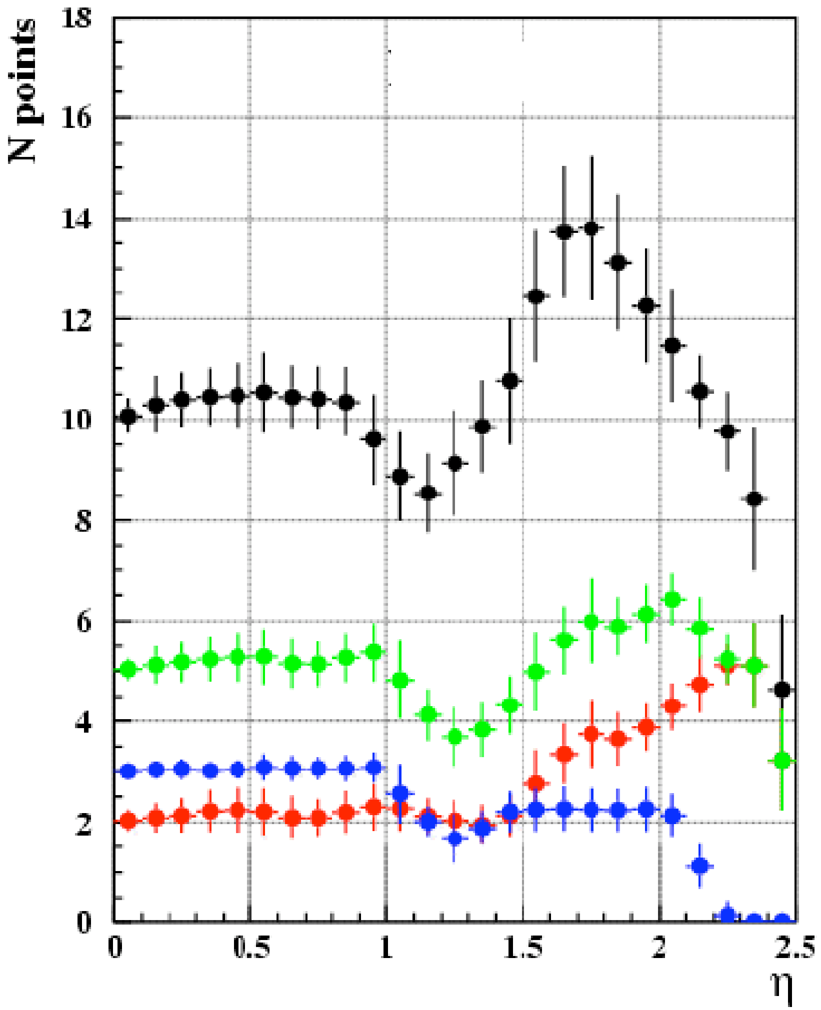
Disk Strip Trackers (TID, TEC)

- Sensors, modules taper as they go out in r. Strips are either radial or small angle to radial
- TEC modules are arranged in petals, 16 of which make up a disk
- The tracker passed an important milestone in March 2006 when the first cosmic muon track was observed in the TEC+
- A total of 400 silicon strip modules were read out with a channel inefficiency of below 1% and a common mode noise of only 25% of the intrinsic noise.



Strip-only Tracking

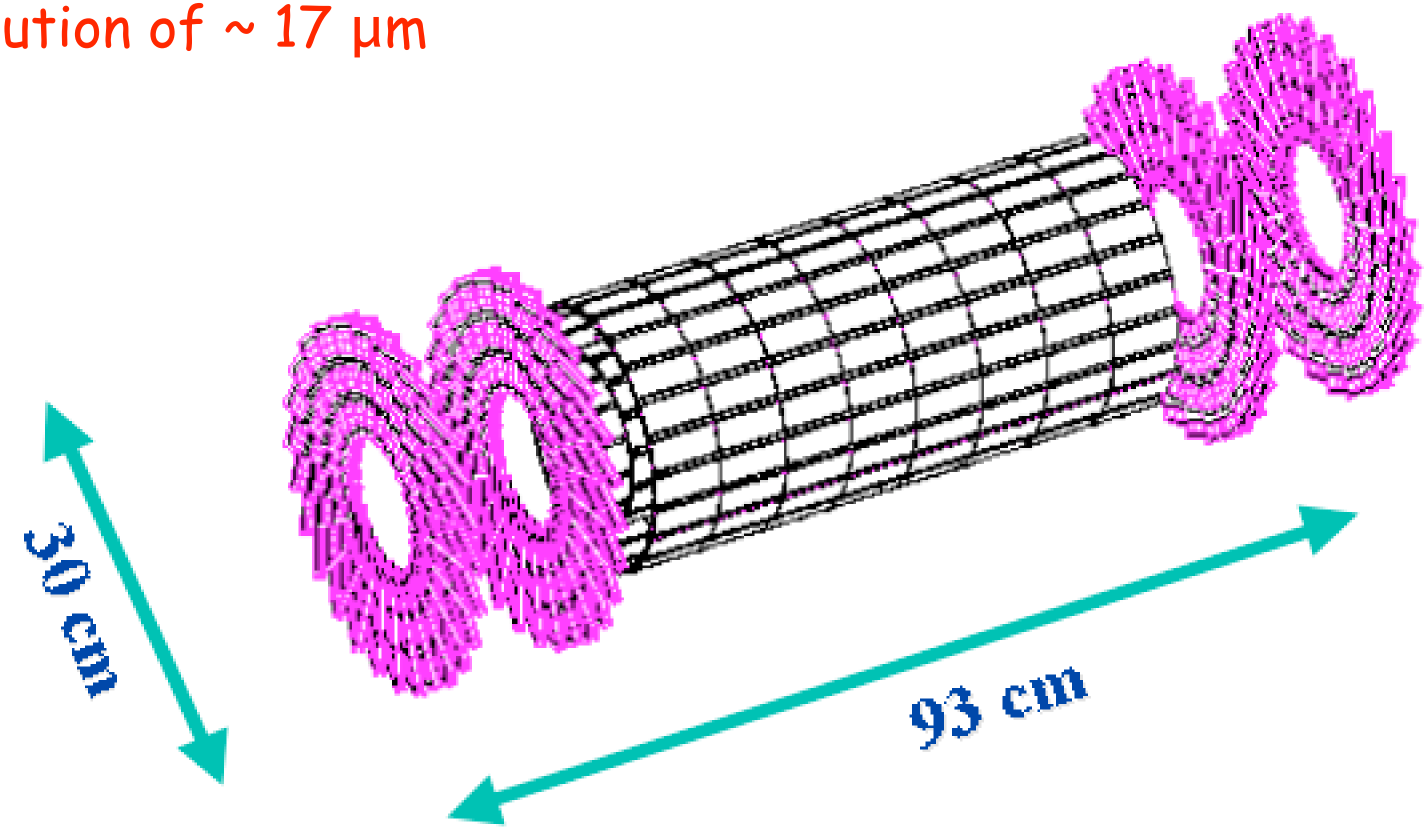
- For LHC 2007 commissioning run, Si strip trackers will be the only complete tracking system (very limited pixel arrays for commissioning only)
- But strips have ≥7 hit coverage to $\eta \sim 2.4$
- Pixel-less tracking algorithms are currently being developed and adapted from existing ones
- 190 GeV H -> ZZ (Z ->μμ) signal is ~50% wider without pixels than with (this can be reduced with a vertex constraint)



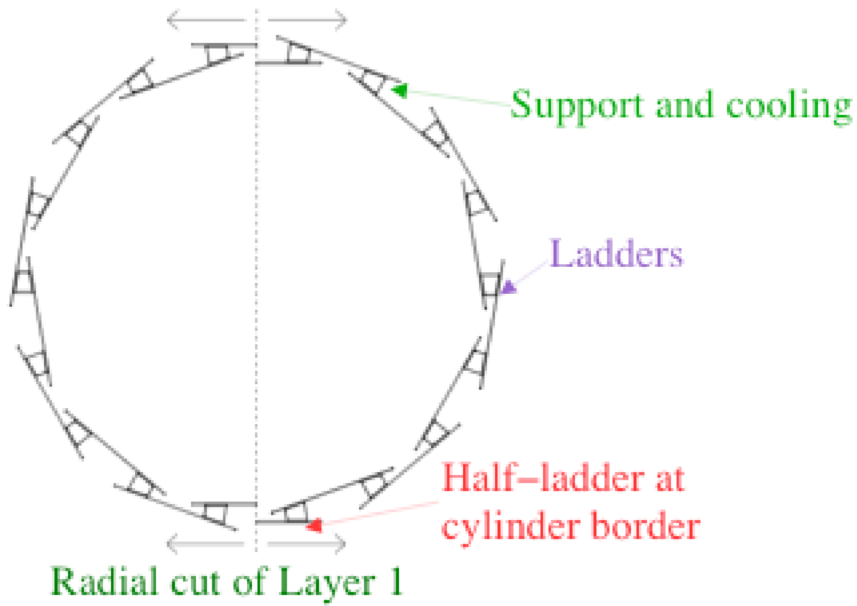
black is total of expected hits vs η, red is thin double-sided hits, blue is thick double-sided, green is sum of double-sided hits

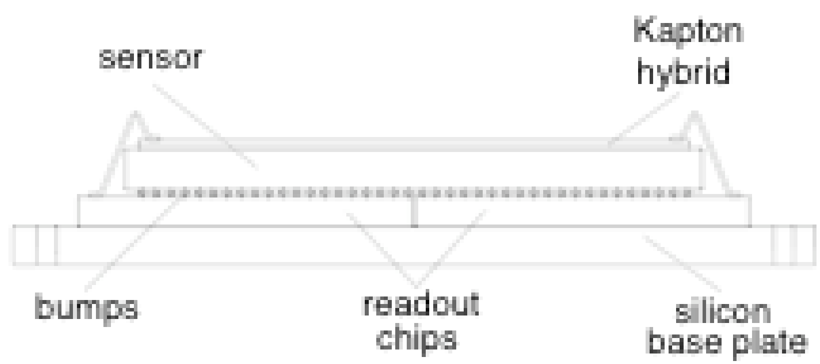
The CMS Pixel Detectors

- 3 barrel layers at r ~ 4.4, 7.3, and 10.2 cm. Length of 53 cm
- Endcap disks at +-34.5 cm, +-46.5 cm
- Pixel size of ~100 μm x 150 μm. 48M pixels in barrel, 18M pixels in endcaps
- 3 high resolution space-points for $\eta<2.2$, 2 for $\eta<2.8$
  r-φ resolution of ~ 10 μm (Lorentz angle of 23° for barrel pixels)
  r-z resolution of ~ 17 μm



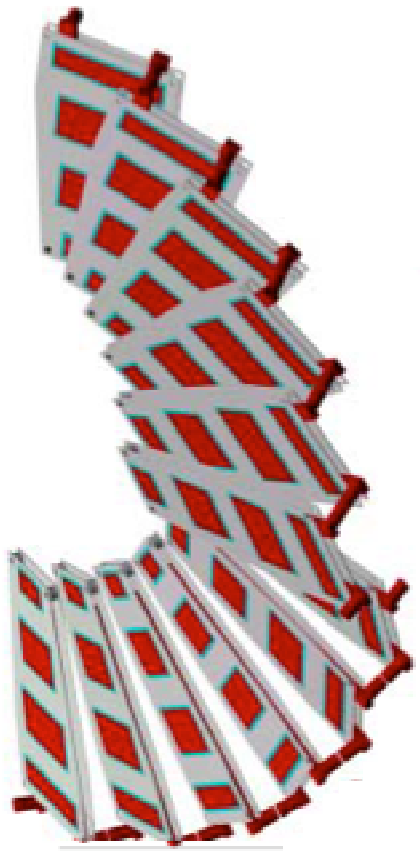
Barrel Pixels

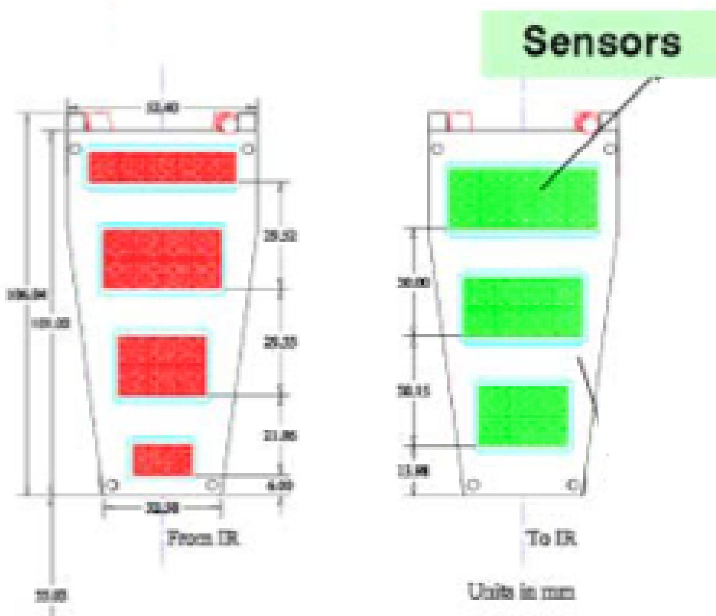




- Si sensors are 1.6 cm x 6.6 cm, 300 μm thick
- 2x8 array of readout chips, Indium bump-bonded to sensors, form modules.
- Sensors have analog readout - analog-coded row/column, pixel pulse height. Shaping time ~ 25 ns (1 bunch x-ing)
- 8 modules per ladder; 800 modules in barrel detector
- 2 data links/module in layers 1 and 2, 1 data link/module in layer 3
- Carbon Fiber support structure with cooling channels

Forward Pixels





- Each forward disk consists of 24 blades
- Blades rotated by 20° for charge sharing (Lorentz angle, track inclination)
- 7 detector modules per blade (4 on front, 3 on back of blade)
- 45 readout chips per blade
- Room for another disk at z = 58.5 cm ($2.0<\eta<3.0$) if needed
- Both Barrel and Forward Pixel full detector assemblies expected to be installed for 2008 LHC Physics Run

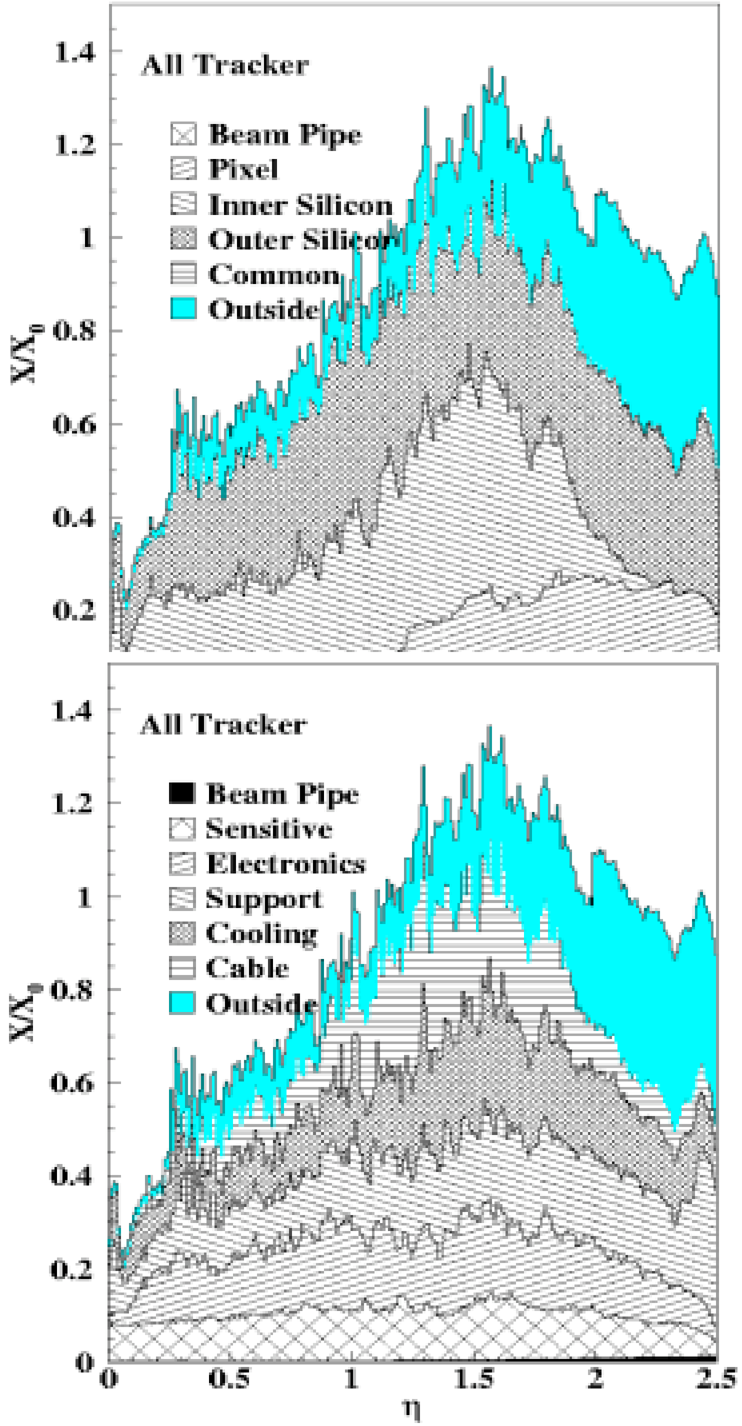
Reconstruction Considerations

- Detector has lots of granularity to deal with occupancy from tracks "not of physics interest" (min-bias pile-up, loopers, out-of-time, back-splash)

- Also has lots of material ($\mu^{\pm}$ scatter, $e^{\pm}$ scatter and bremsstrahlung, $h^{\pm}$ scatter and interact!). Kalman Filter final track fit accounts for scattering and dE/dx

- Interaction lengths have similar distribution as radiation lengths (right).
  Peak of λ/λ_0~0.45 at η~1.6

- In many ways more difficult to deal with - radically alters/kills tracks (many hadrons don't get to outer layer of strip tracker)

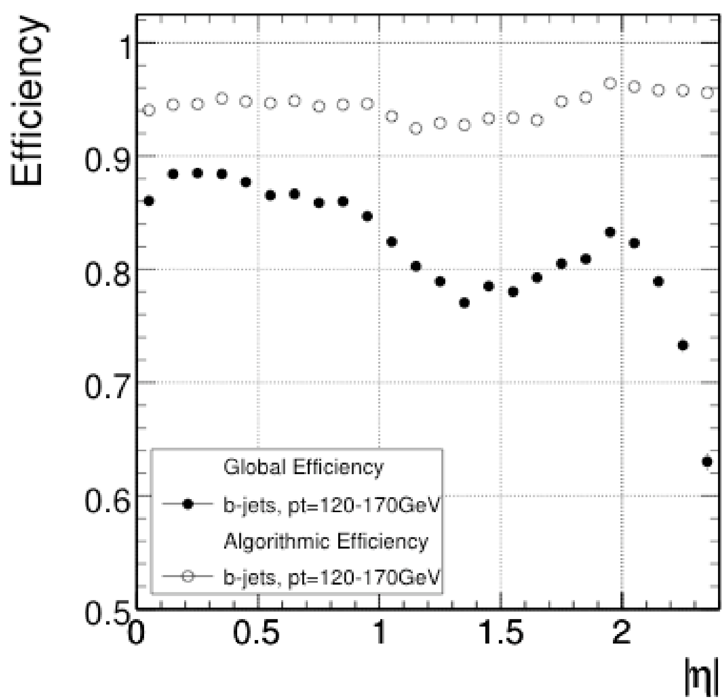


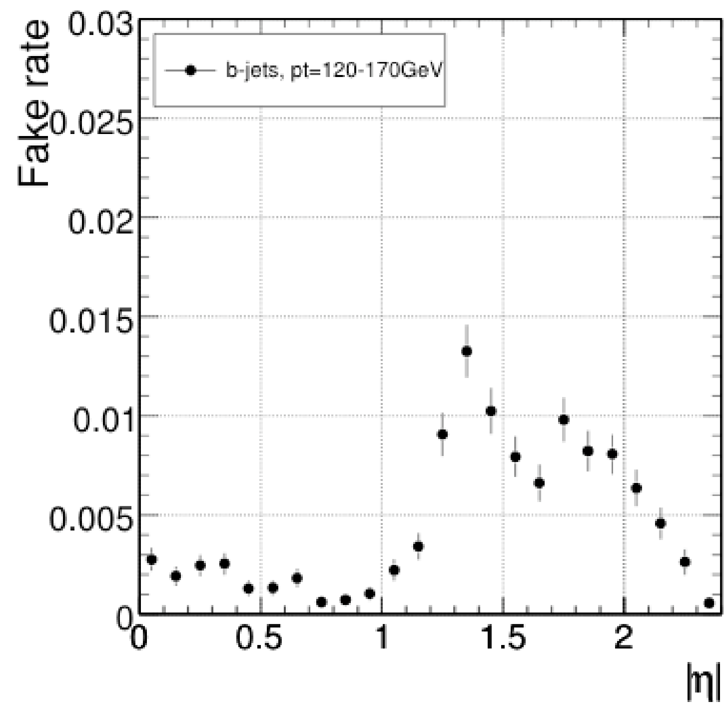
Track Reconstruction Software

- Primary Pattern Recognition the Combinatorial Track Finder (CTF)
- Seeded from hit pairs in 2 pixel detector layers within acceptable windows. Even though most hits, pixels have lowest occupancy and tracks haven't interacted/decayed yet
- Can tighten seeding by using primary vertex
- Trajectory building -> propagate seed to new (compatible) layer, update parameters and errors (Kalman) with all compatible hits (new trajectories)
  - also make new trajectory with "null" hit in case of inefficiency
- Propagate these trajectory candidates to next layer in parallel (avoid bias)
- Trajectories killed if χ^2 too big or too many missing hits
- Final trajectories are Kalman fits of tracks - smooth with parameters of trajectory propagated backwards

Track Efficiency and Fake Rate

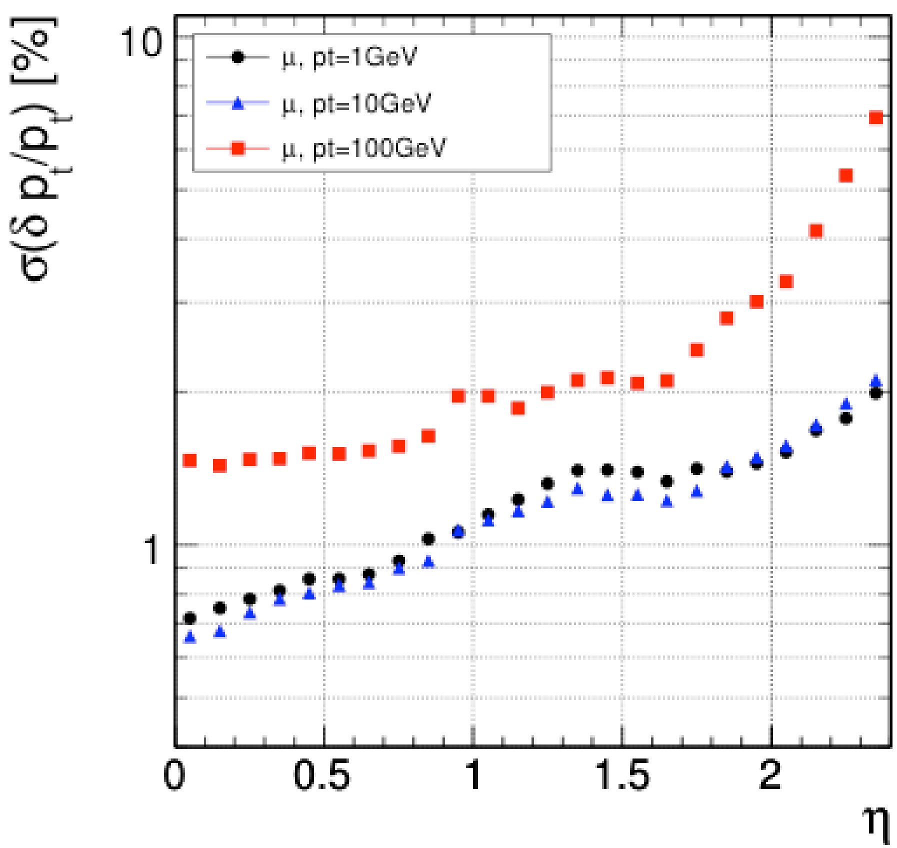
- CTF has been CMS standard tracking code for >5 years now; constantly being improved and extended
- Most of its time is spent in trajectory building
- Global efficiency ≥99% for high p_T μ with η < 2.0
- Below left is global and algorithmic (fraction of tracks algorithm should find) efficiency for a hard case - tracks in high p_T (120-170 GeV) b jets with low luminosity pile-up added
- Right is fake rate for tracks in these jets

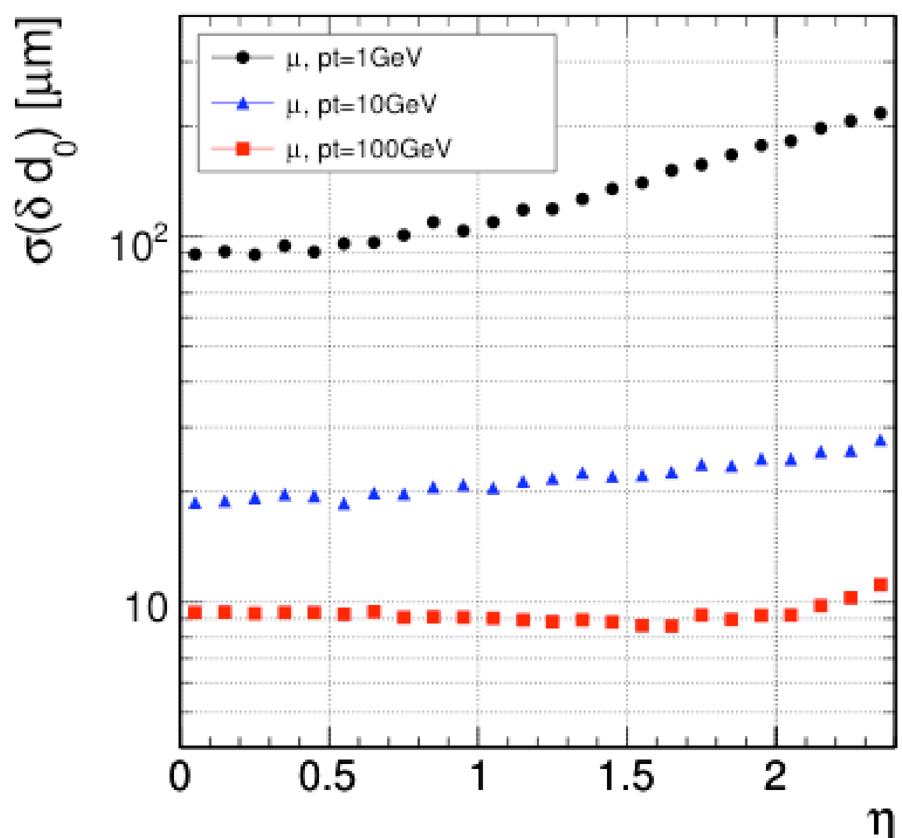




Track Parameter Resolutions

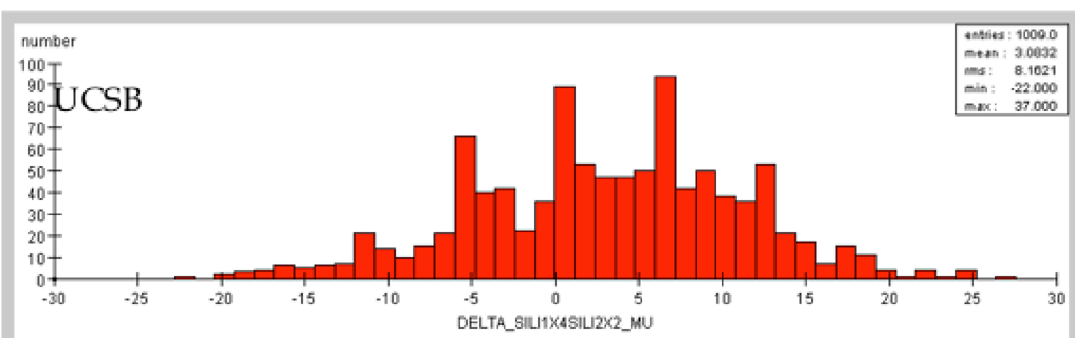
- The combined trackers provide ~ 2% or better p_T resolution for p_T = 100 GeV/c tracks out to η~1.25 (better for lower p_T)
- For p_T = 10 GeV/c tracks:
  - $\sigma(d_0)$ < 25 μm out to η = 1.5; ~ 30 μm at η = 2.4
  - $\sigma(z_0)$ < 60 μm out to η = 1.5; ~ 150 μm at η = 2.4

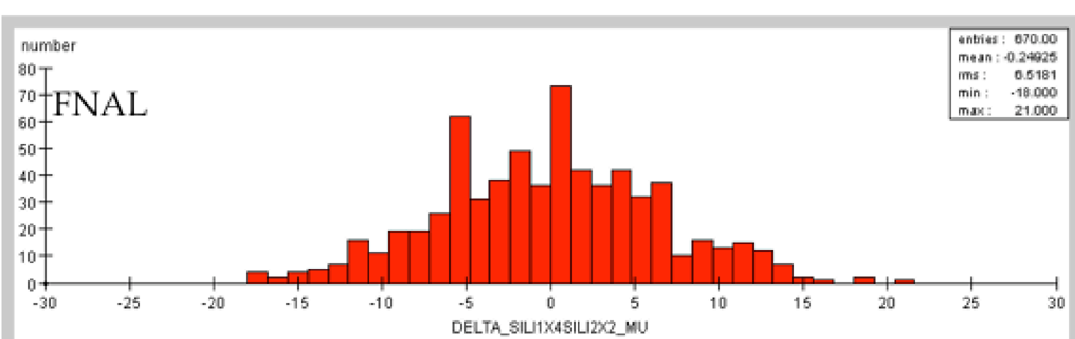


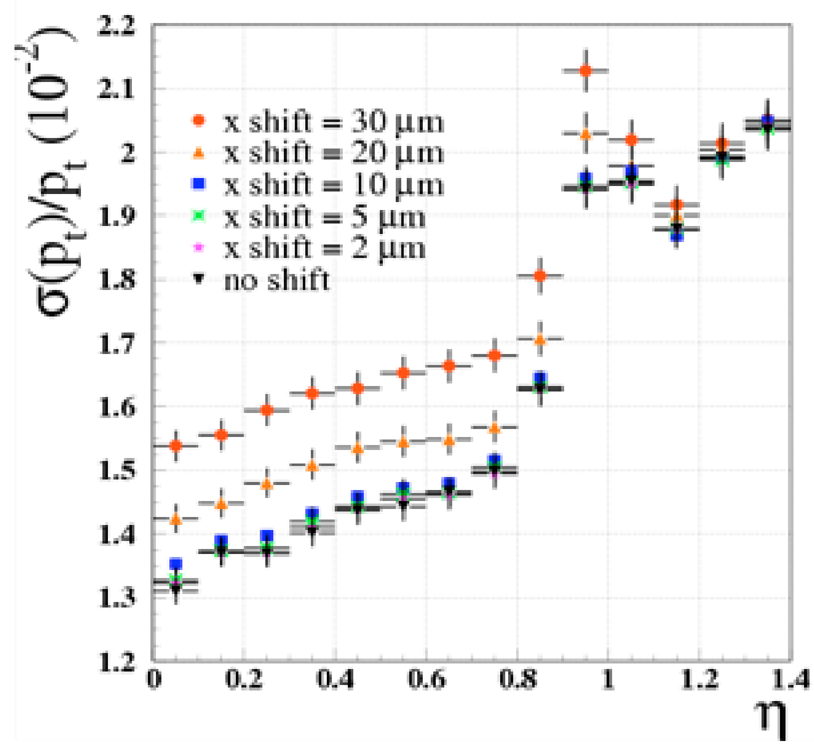


Alignment Requirements

- Wafer positions carefully measured at all stages of assembly. Below left are x (μm) of sensors in TOB modules - $\sigma < 10$ μm
- This level of misalignment wouldn't even be seen in p_T resolution if left uncorrected (below right), but 2 or 3 times this would
- Sensor global placement to ~ 100 μm at the beginning - will need track-based alignment to get it down to ~ 10 μm
- There is a laser system (LAS) for hardware alignment of the strip detectors - will monitor long-term shifts of large structures after the detector is assembled





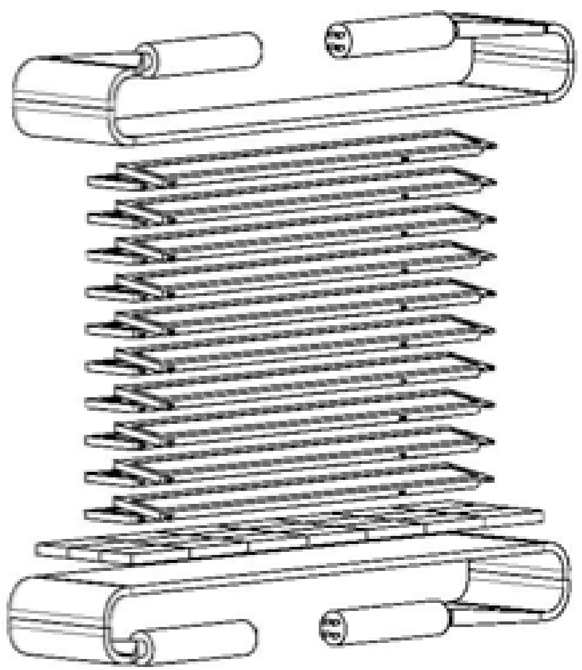


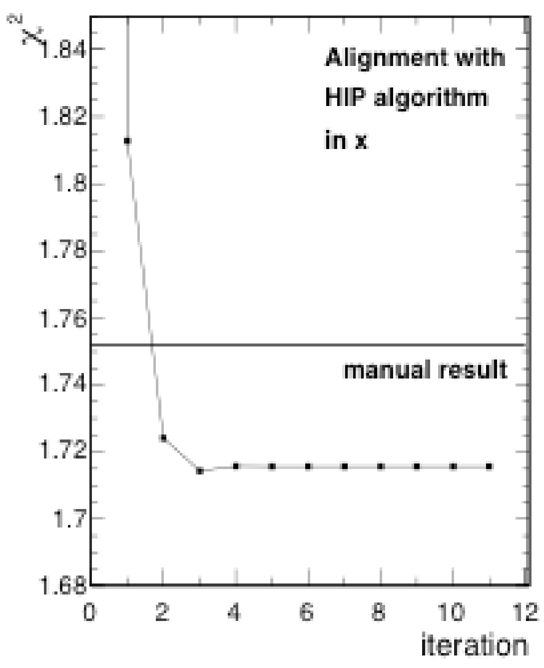
Alignment Algorithms

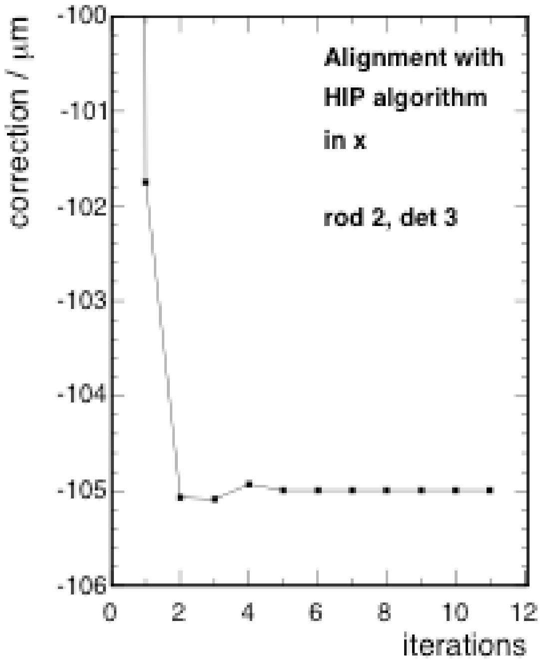
- CTF shown to work well with misalignments up to 1 mm at low luminosity -> this is the starting point for track-based alignment of lots of modules (~20k including pixels)
- Several different track-based alignment algorithms currently being developed:
  - HIP: Hits and Impact Points collected for each alignable sensor. Analytic functions describe residuals for up to 6 alignment parameters/module (χ^2 min of 6N parameters). Inverts block diagonal matrix
  - Millepede: Fits to 6N + track parameters simultaneously. Inverts very large matrices. New version ~ ×1000 faster than previous, adapted to run on O(10k) rank matrices
  - Kalman Filter: update alignment params after every track; correlations without inversion of large matrices
  - Simulated Annealing

Alignment Tests with Cosmic Rack

- The CRack is a test-stand for RODs which mimics a wedge of the TOB (Sept 2004 test-beam run) or more (see below left) - also a cosmic telescope
- CRack tracks (reco-ed using a modified CTF and identical software alignment elements) provide some tests of alignment algorithms
- Easily aligned manually. HIP, aligning in x only, produces better results and converges quickly (x and yaw only marginally better)
- Millepede applied to same data produces consistent results

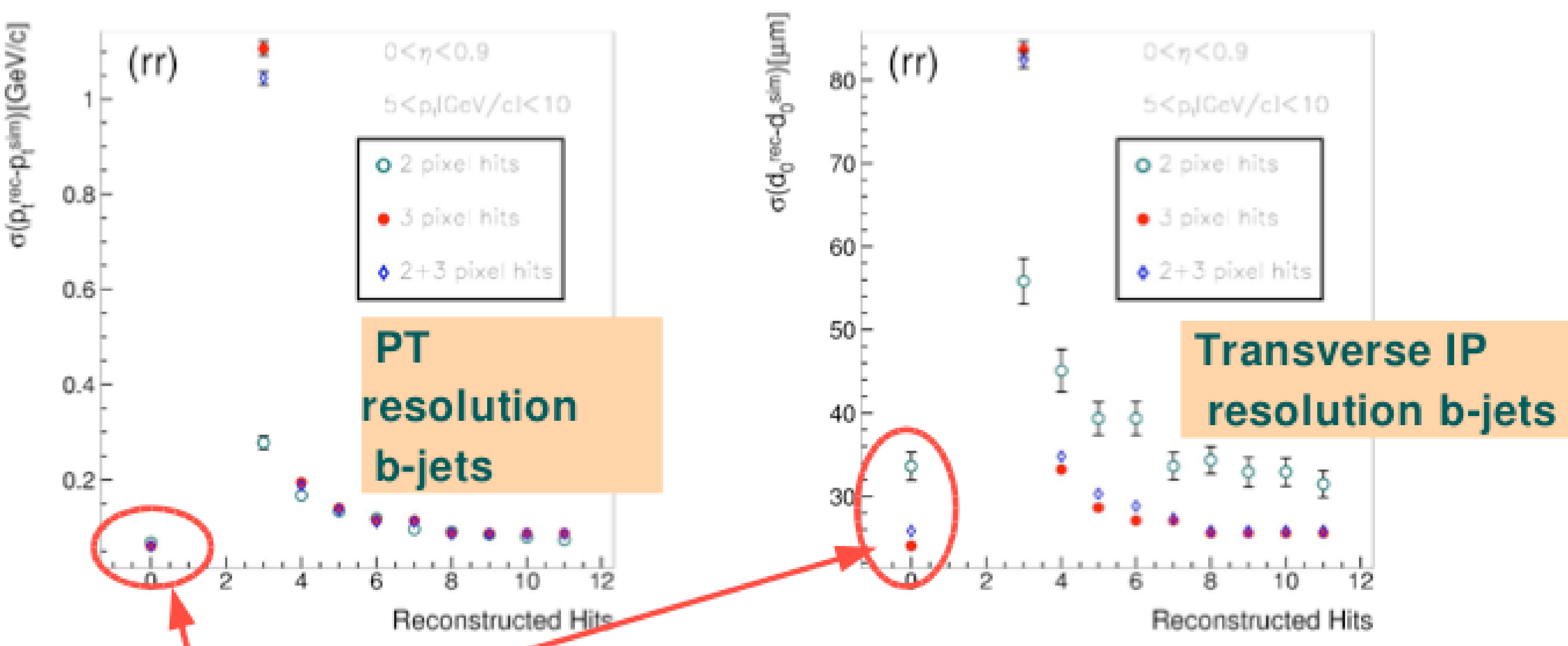






Fast Track Reconstruction

- Can use CTF seed finding, trajectory building, and fitting code in High-Level Trigger (HLT)
- Full tracking too slow but can stop as soon as parameters get good enough for trigger purposes (truncate trajectory building, where most tracking time spent). ~5-6 hits usually enough



Tracking results with all possible hits included

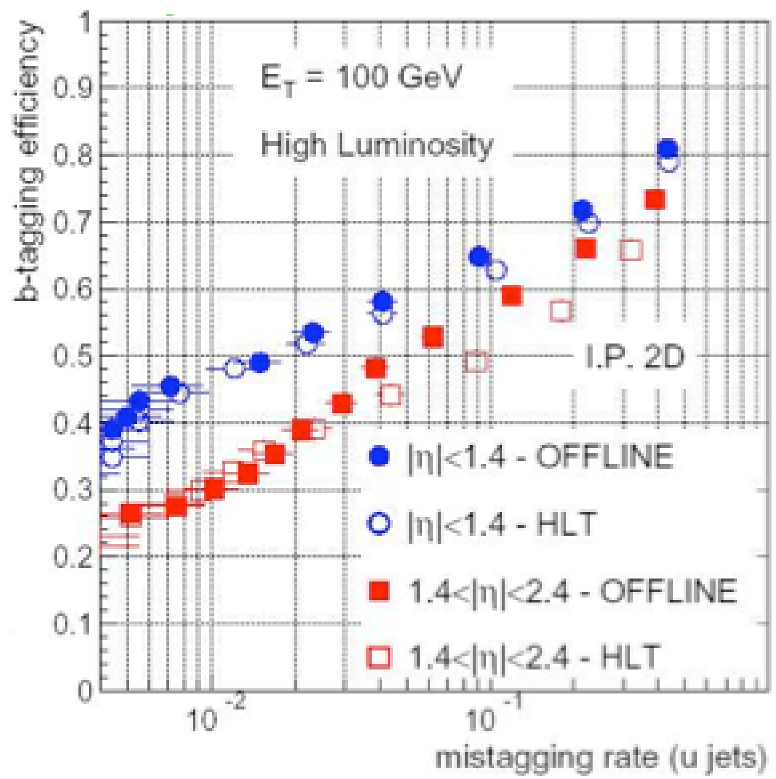
Impact Parameter b Tagging

- If combined with regional tracking (looking for tracks only in a region defined by trigger lepton or jet) can consider doing b-tagging in HLT with fast partial tracking

- Performance with partial tracking run out to 7 hits (open symbols) not much worse than that for full offline tracking (solid symbols) for simple impact parameter b-tag

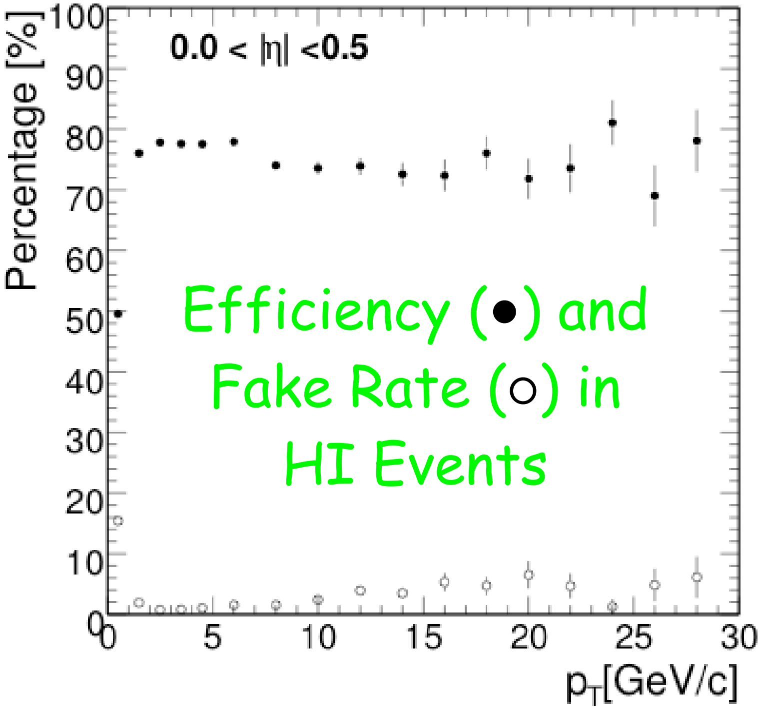
- This will really rely on having the alignment under control

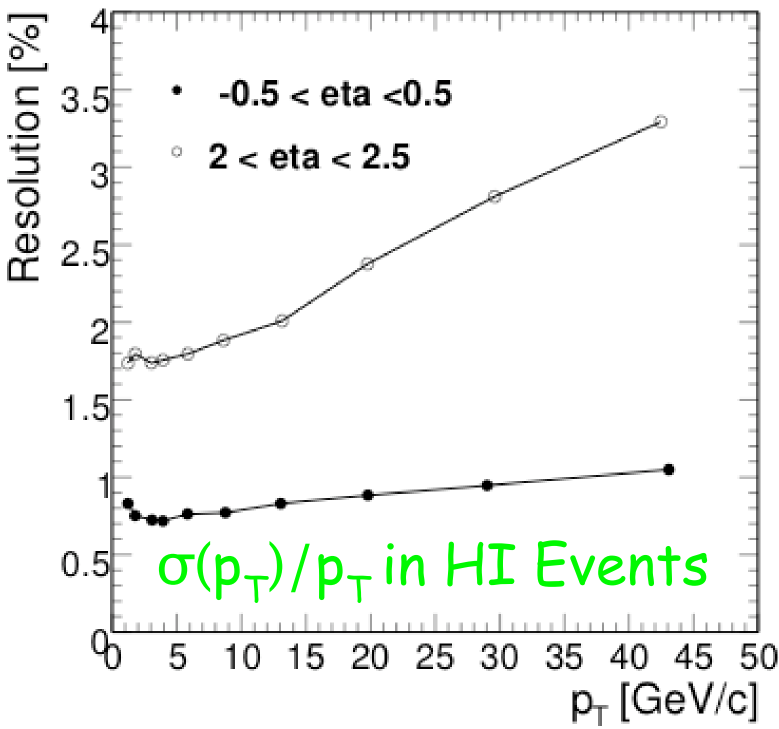
b-tag eff vs mistag rate for u-jets for regional, partial (7 hit) tracking.
Tag: 2 trks with IP/σ > cut



Heavy Ion Tracking Performance

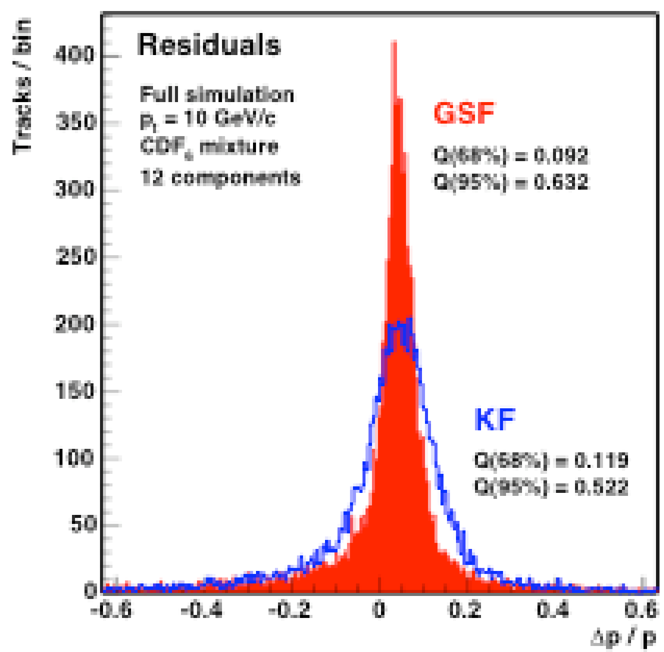
- In central PbPb Events we expect very high track densities:
  - dN/dy_{PbPb} ~ 3500 (dN/dy_{pp} ~ 7)
  - HI tracking must be robust at high occupancy (~1% in pixels, up to 50% in strips)
- Specialized HI tracking algorithm:
  - Seed tracks with pixel triplets (low occupancy, good initial estimate of track parameters
  - Use Kalman Filter to propagate tracks into strips. Special error assignment for merged hits
  - Select only one track per seed by best X^2
  - Perform final fit with stereo layers "split"
  - To reject fakes, require > 12 hits (out of 17), $P(X^2) > 0.01$, $d_0/\sigma > 3$
- Excellent performance even at highest track densities

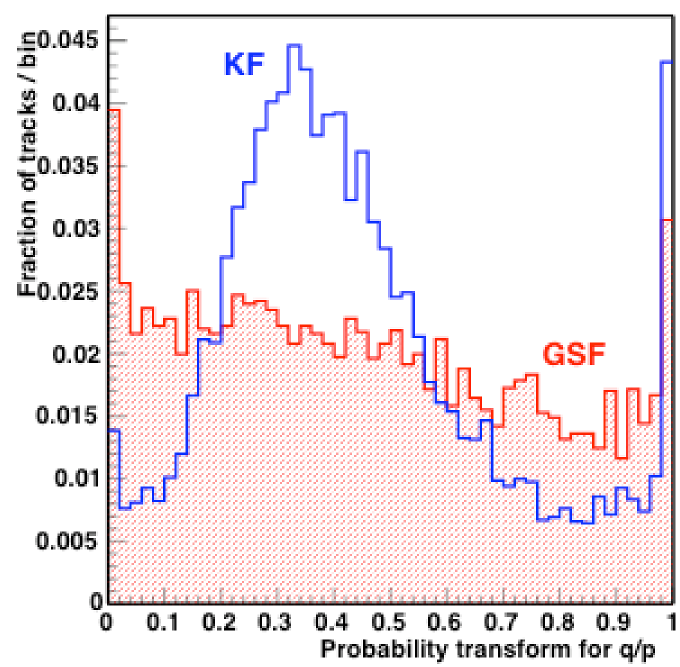




Gaussian Sum Filter

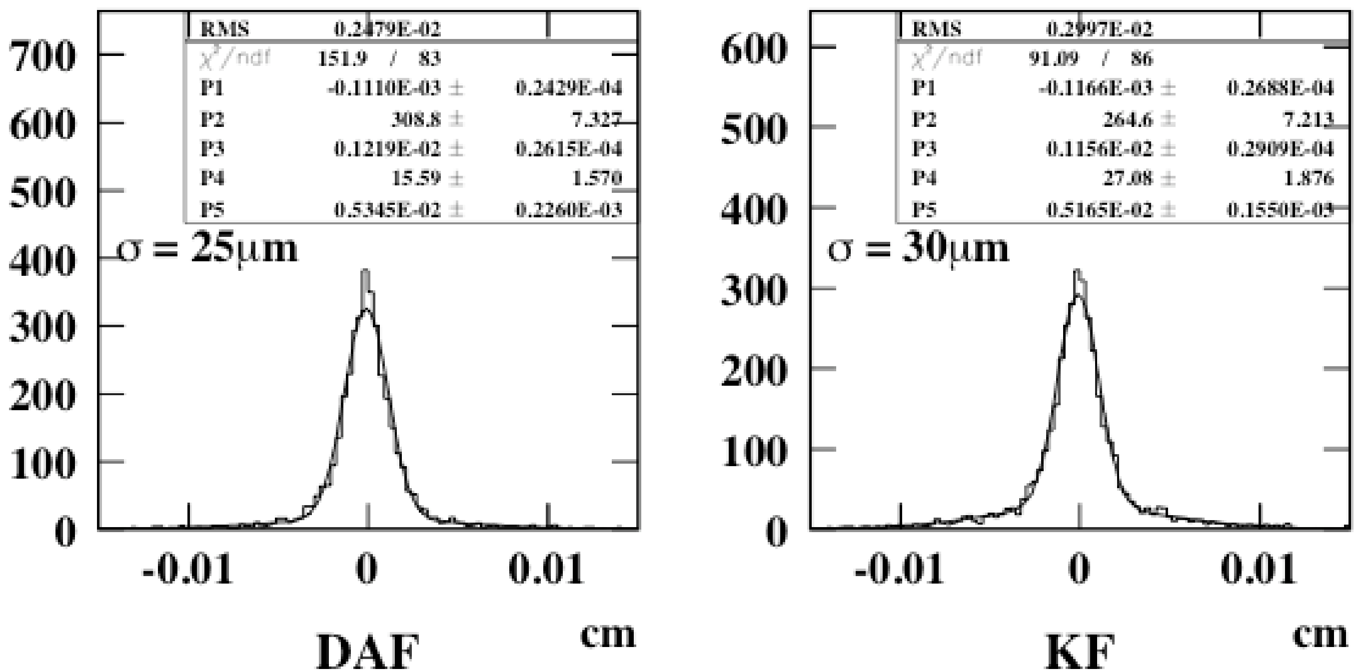
- In Kalman Filter (KF) multiple scattering and Energy loss variance are (well) treated as Gaussian “process noise”
- Some processes, like bremsstrahlung, are inherently non-Gaussian (Bethe-Heitler) but can be approximated as a sum-of-Gaussians
- Introduce new components (multiplication of # of states). After each update recalculate weights (non-linear). Retain only high probability components (in plot limited to 12)
- Increases fit time by (unoptimized) factor of ~200. Use only on $e^{\pm}$ candidates of interest. But also significantly improves parameters, pulls





Deterministic Annealing Filter

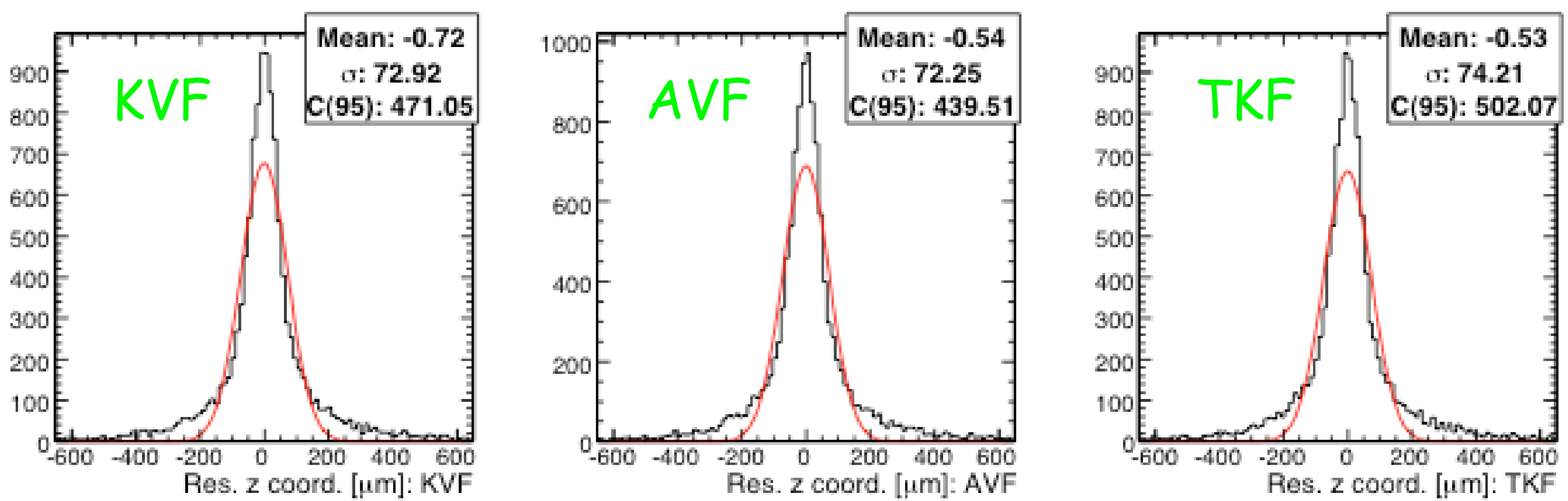
- Assignment of wrong hit in pattern recognition causes tails in parameter distributions; right hit is often close-by
- DAF (equivalent to “Elastic Arms”) allows multiple hits/layer to be assigned to a track. Competing hits assigned (normalized) probabilities based on residual to track
- KF fitter/smoother run to convergence; recalculate probabilities (non-linear)
- Also “anneal” fit while converging ($V \to \alpha V$, $\alpha = 81 \to 1$) to keep out of local minima. Below is transverse impact param (d_0) for p_T > 15 GeV tracks in high E_T b jets. Also flattens $P(X^2)$ distributions



Vertex Fitting Algorithms

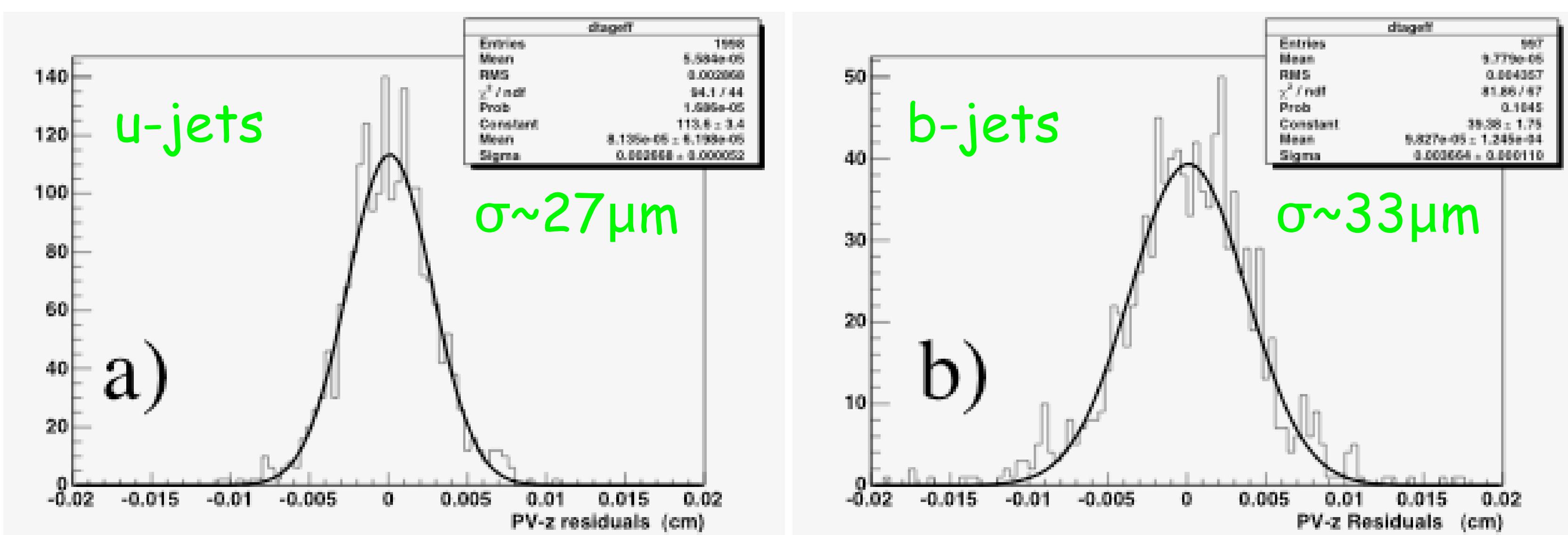
- Several different vertex fitting algorithms being investigated:
  - Kalman Vertex Fitter - The standard. Linear. Refit of track with vertex constraint. But sensitive to tails on track param resolutions and tracks not from vertex
  - Trimmed Kalman Fitter - discards tracks with < 5% (typical) probability of coming from vertex
  - Adaptive Vertex Fitter - iterative KF where tracks are weighted by $w(d/\sigma, T)$. T changes with iteration (anneals)
  - Gaussian Sum Vertex Fit - add mixture of Gaussians to track error distributions (for tails)

z(fit)-z(true)
$B_s \to \psi\varphi$ vertex fit



Primary Vertex Finding

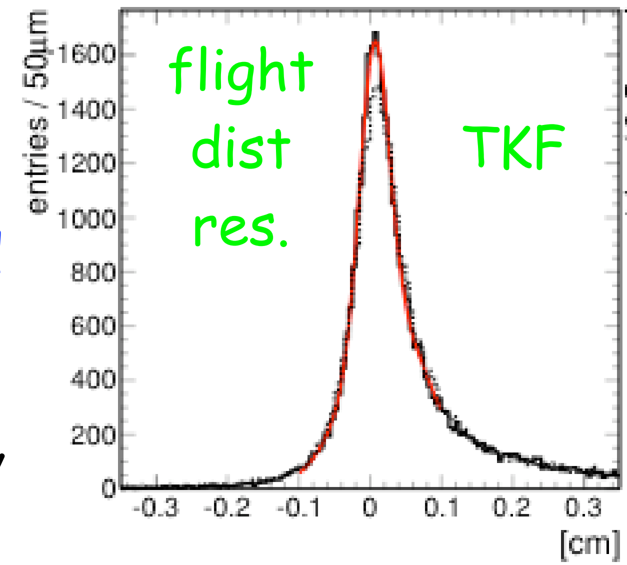
- Primary vertexing moves from off-line into HLT so information available there and for seeding full tracking
- A tighter variant of fast tracking uses triplets of hits in the pixel detectors only
- After cuts on p_T and impact parameter, vertices are formed using a histogramming method (z impact parameter) or a variant of Trimmed KF
- Trimmed KF shows slightly better results. Efficiencies ~80-100% for various physics processes (low multiplicity like H -> ϒϒ harder)
- Typical z_{PV} resolutions at low luminosity shown below. Results consistent with PV reconstruction with full tracking

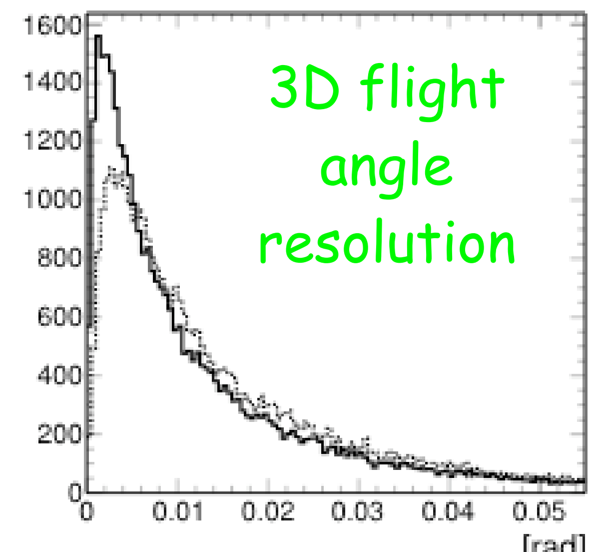


Jet Vertex b Tagging

- Two vertex algorithms have been studied for finding secondary vertices (b, c decays) - the Trimmed Kalman Vertex Fitter (TKF) and a Tertiary Vertex Finder (TVF)
  - TVF based on Kalman but uses tracks from tertiary (b->c) that might otherwise be trimmed away from secondary vertex
  - Also some tertiary tracks assigned to secondary vertex (and bias reconstructed vertex forward) now have another place to go
- With typical secondary vtx cuts ($L/\sigma > 3$, away from PV and beampipe, mass cuts), have ~63% eff for 90% purity with TKF (resolutions at right) for 20-70 GeV p_T b-jets in barrel, slightly higher with TVF

Also investigated effect of short-term misalignment (dashes)





Conclusions

- The strip tracker is entering final assembly stage. The pixel detectors appear on-schedule for 2008 LHC Physics run
- Various early tracker subsystems beginning to take cosmics. The Magnet Test/Cosmic Challenge should start seeing cosmics in (very limited) tracker with full field soon
- The main tracker pattern recognition (CTF) and Kalman final fit are quite robust and adaptable:
  - It can be used with less than the full detector for speed (for the HLT) and produces quality results
  - With modifications it can handle the dN/dy ~ 3500 of HI interactions
  - It can be adapted to deal with complex, non-Gaussian processes and resolution tails in track fitting and vertexing
- The tracking and vertexing code is being ported to a new, more modular event data structure (CMSSW). The basic functionality is there now, ready for validation. Now need to port higher-level code (like GSF - easier) and resume developing
- The CMS tracking system is beginning to come together in a hurry!